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AUSTRALIA

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PROVISIONAL SPECIFICATION

Applicant(s):

THE UNIVERSITY OF SYDNEY

Invention Title:

OPTICAL DEVICE AND PROCESS

The invention is described in the following statement:

Optical Device and Process

Field of the invention

The present invention relates broadly to an optical device comprising a waveguide and a process for fabricating the same.

Background of the invention

Grating confinement refers to the confinement of optical waves in a medium by means of reflection of the waves off grating reflectors at the boundaries of the medium under a Bragg condition. The grating-confinement theory has been described e.g. in R.J Lang, K. Dzurko, AA. Hardy, S. Dematrs, A. Schoenfelder, D.F. Welch, "Theory of grating-confined broad-area lasers" IEEE J. Quantum Electron., 34 (11), pp.2196-2210.

The only application of grating-confinement in an optical device is the design of a a-DFB laser in which a planar optical resonator is used to achieve grating ring DFB lasing. As illustrated in Figure 9, the resonator 212 comprises four gratings 200, 202, 204, and 206 formed in an optical waveguide layer 208.

The gratings 200, 202, 204, and 206 consist of planes of constant refractive index which are perpendicular to the plane of a substrate 214 and define a central cuboid 210 between them. The period of gratings 200 and 204 is ½ of the period of gratings 202 and 206 and the two groups of gratings are disposed orthoganal with respect to Each other. The resonator 212 can be used as a grating ring laser because of non-zero transmission of the gratings as indicated by arrow 216.

Importantly, in the prior art, the resonator 212 is fabricated using complex deposition and etching sequences to construct the gratings 200, 202, 204, and 206. Such a process is time-consuming and requires a complex deposition and etching sequence. This has resulted in the above

mentioned limited application of the grating confinement theory in the design of optical devices.

The present invention seeks to provide an alternative process for fabricating devices which utilise grating confinement and new devices made by the process.

Summary of the Invention

The present invention provides an optical device comprising a waveguide of photosensitive material; at least one grating structure formed by UV-induced refractive index variations in the waveguide; and wherein the grating structure is disposed to confine to a selected path in the waveguide light of a predetermined wavelength entering the waveguide at a predetermined angle of incidence on the grating structure.

Because of the angular dependence of the accepted wavelength in the grating confined waveguide such devices can e.g. depend on angular sweep to isolate wavelengths or signals.

The grating structure may comprise a continuos grating. Alternatively, the grating structure may comprise two gratings which mirror each other.

In one embodiment, the grating structure comprises regions of constant refractive index which extent in the propagation direction of the waveguide.

The regions may extend parallel to the propagation direction.

The regions may extend cylindrically parallel to the propagation direction.

The regions may extend elipsoidically parallel to the propagation direction.

The device may further comprise at least one optical reflector disposed in a direction transverse to the propagation direction to aid in confining the light to the path.

The device may comprise two or more grating structures angularly disposed with respect to each other to channel the light around the selected path.

Accordingly, different confinement conditions may be realised at different boundaries of the waveguide.

The grating structures may be formed by UV-holography.

The gratings may be chirped gratings.

The gratings may be sampled gratings.

The device may be a filter, a resonator, or a sensor.

In one embodiment, the device is a sensor further comprising means for measuring an intensity of the light at a predetermined point along the selected path for determining changes in the intensity due to induced changes in confinement conditions of the sensor.

The changes may be induced by gas molecules entering the waveguide.

The present invention may alternatively be defined as providing a process for fabricating an optical device comprising a waveguide of photosensitive material, the method comprising the step of forming at least one grating structure by UV-induced refractive index variations in the waveguide; and wherein the grating structure is disposed to confine to a selected path in the waveguide light of a predetermined wavelength entering the waveguide at a predetermined angle of incidence on the grating structure.

Preferred forms of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Brief Description of the Drawings

Figure 1 illustrates in an isometric view a method of fabricating a grating confined waveguide embodying the present invention.

Figure 2 illustrates in an isometric view another method of fabricating a grating confined waveguide embodying the present invention.

Figure 3 is a schematic drawing in a cross-sectional view illustrating a device embodying the present invention.

Figure 4 is shows a plot of resonant angle against grating period for a grating confined waveguide.

Figure 5 is a schematic drawing in an isometric view illustrating a device embodying the present invention.

Figure 6 is a schematic drawing in a top view illustrating a device embodying the present invention.

Figure 7 is a schematic drawing in a cross-sectional side view illustrating a device embodying the present invention.

Figure 8 is a schematic drawing in an isometric view of a prior art resonator structure.

Figure 9 is a schematic drawing in an isometric view of a device embodying the present invention.

Detailed Description of the Preferred Embodiments

In Figure 1, a waveguide 10 in the form of a layer of photosensitive material has been deposited onto a substrate 12, eg. a silicon wafer having a native oxide layer for optical isolation of the waveguide material 10.

A UV beam 16 from a UV source 14 is focussed (through optical elements 18) in the plane of the waveguide 10. The substrate 12 can be laterally moved as indicated by arrows 20 and 22 to effect writing of planes indicated by lines 24 of a first grating 26 of a grating structure 27, through UV-induced changes of the refractive index of the waveguide 10.

After completion of the first grating 26, a second grating 28 of the grating structure 27 is written by appropriate moving of the substrate 12.

Light of a predetermined wavelength entering the waveguide 10 at predetermined angles of incidence on the gratings 26, 28 are confined to a path extending in the propagation direction 30 in the plane of the waveguide 10. The propagation characteristics of the waveguide 10 will

therefore depend on the wavelength of a light signal 31 and an angle θ under which it enters the waveguide 10.

It is noted here, that in the planar structure described above the grating confinement is limited to one-dimension in the plane of the waveguide 10. However, it will be appreciated that waveguides can be produced in a photosensitive waveguide material that are grating confined in two or three dimensions.

For example, as illustrated in Figure 2, holographic UV grating writing techniques using a phase mask 40 can be used to produce a waveguide 42 (propagation direction as indicated by arrow 41) within a block 44 of photosensitive waveguide material which is grating confined in two dimensions through gratings 46, 48 of a first grating structure 47 and gratings 50, 52 of a second grating structure 51 respectively.

It is noted that the one or more of the grating structures of a device could alternatively comprise a continuos grating whilst still effecting confinement of light of a predetermined wavelength entering at a predetermined angle of incidence on the grating structure.

E.g. the resonator 250 shown in Figure 9 comprises two continuos grating structures 252, and 254 to effect ~~channelling of light 256 of a predetermined wavelength~~ entering the resonator 250 at a predetermined angle of incidence on the grating structures 252 and 254 around a ring path 258.

Grating confinement can also be achieved in an optical fibre, e.g. using a cylindrical grating structure 120 around a guiding core 122 (propagation direction perpendicular to the drawing plane) of an optical fibre 124 as illustrated in Figure 3. The grating structure 120 effects confinement to a path extending in the propagation direction of light of a predetermined wavelength entering

at a predetermined angle of incidence on the grating structure 120.

It will be appreciated by a person skilled in the art that for a non-cylindrical grating structure confinement conditions can vary in different radial directions.

The underlying principle of grating confined waveguide propagation is the Bragg condition. For a ray travelling in a medium of index n, peak reflectivity occurs when the wavelength λ satisfies:

$$\lambda = 2n\Lambda\theta / m \qquad (1)$$

where m is the diffraction order of the grating and θ is the angle of the ray with respect to a single groove of the grating. This single equation contains within it the entire properties of grating confinement such as e.g. so-called photonic crystal fibres.

Figure 4 shows the plot of resonant angle against grating period for the wavelength regime 1200-1600 nm for 1st, 2nd and 3rd order grating diffraction. At longer periods, variations in the resonant angle converge to within a few degrees, although the effect is largest for the 1st order. The physical interpretation is that for a large number of wavelengths the incident angle is approximately the same equating with similar diffraction properties. Therefore grating confinement will occur over a large bandwidth for a small input coupling angle at longer periods under identical launch conditions. Outside this regime radiation loss will occur.

Other interesting properties are noted. There exist other regimes of incident angle at which total internal reflection can occur to enable propagation along the grating confined waveguide. Light coupled into higher diffraction orders at much larger incident angles can also satisfy the Bragg relation, giving rise to higher order bandgaps. The effective coupling strength is reduced for

higher order mode propagation in these regimes and is therefore characterised by larger mode areas. Since the effective index is different, it is possible to have fundamental-like mode behaviour simultaneously with different propagation properties. Thus e.g. photonic fibres have interesting launch regimes which are unlike conventional effective index fibres. These regimes exist because there are angular photonic bandgaps at which light cannot propagate through the surrounding grating cladding. Further, these bandgaps are robust and do not change much in angular properties with increasing period and will therefore be relatively insensitive to bend loss at longer periods.

The angular photonic bandgap is described by the angular reflectivity of the grating. This reflectivity bandwidth can be extremely small, depending upon the dimensions of the grating, its coupling coefficient, and the angle of incidence. For either normal (incident angle, θ = 90°) or angled incidence, the power reflectivity is given from coupled mode theory as

$$R = \left| \frac{K \sinh SL}{S \cosh SL + i\Delta\beta \sinh SL} \right|^2 \qquad (2)$$

where

$$S \equiv \sqrt{K^2 = (\Delta\beta)^2} \qquad (3)$$

K is the angle-dependent coupling coefficient for the grating, L is the length of the grating and Δβ is the detuning of the wavevector, defined by

$$\Delta\beta = \frac{m\pi}{\Lambda} - \frac{2\pi n}{\lambda} \sin\theta \qquad (4)$$

Peak reflectivity occurs for Δθ = 0 and declines as Δθ exceeds the magnitude of K. It is readily shown in grating confined waveguides that the angular acceptance of the reflectivity narrows considerably, with deviation away from

near normal incidence (as indicated by the decreasing slope of Figure 4). Consequently, the higher order photonic bandgaps will be broader and less spatially selective and this may have implications for the robustness of singlemode operation for large input angles. The variation of detuning $\delta(\Delta\beta)$ with angle $\delta\theta$ is easily calculated from above:

$$\frac{\delta(\Delta\beta)}{\delta\theta} \approx -\frac{2\pi n}{\lambda}\cos\theta \qquad (5)$$

From this sensitivity to the capture angle it is possible to vary the angular dispersion significantly by appropriate selection of the period. Since the angle of incidents are similar at longer periods (Figure 4) the propagation constants, and therefore the sensitivity to capture angle, tend to converge with increasing grating period - it is therefore possible to achieve a dispersion flattened profile of the type found numerically.

Note that even for light guided solely under the effective index picture when the core index is higher than the surrounding cladding, unless the mode vector has an angle resonant with that of the grating, light can quickly couple to radiation modes and leak out. Further, this intolerance to the mode angle gives rise to the high spatial selectivity of these angular bandgaps such that single-moded propagation is robust especially for long grating periods. The mode profiles that are supported will therefore resemble the geometric positioning of the gratings radially around the core region and should differ from conventional waveguide guidance where such strict restrictions do not exist.

By recognising the importance of diffraction in a periodic lattice it is easily shown that grating confined propagation is readily achieved in so-called photonic crystal fibres. Further, the associated angular photonic bandgaps are responsible for a range of phenomena that

distinguish these fibres from conventional effective index fibres. Extending the applications to resonators made up of these fibres, very interesting behaviour is predicted to occur as a result of the strict vector angles of the propagating modes, including ring-like resonances when the end reflectors are tilted. The polarisation properties of such structures may also differ to conventional resonators and an entire new class of passive and active filters and resonators are possible.

In Figure 5, a resonator 81 can be utilised for WDM (wavelength division multiplexing) filtering if the grating periods (which may be chirped) of gratings 82 and 84 of a first grating structure 83 and of gratings 86 and 88 of a second grating structure 87 are carefully selected such that a ring resonance is different for different wavelengths and therefore the outputs are spatially at different points. This is schematically illustrated by paths 90, 92 and example outputs 94, 96. The grating structures 83 and/or 87 may be sampled grating structures.

Complex design with the use of sampled profiles etc. can be used to achieve WDM operation. In particular the angular dependence means that it may be possible to get much more closely spaced peaks with higher contrast than conventional normal incidence. It is noted that this is also applicable to fibre (e.g. photonic crystal fibres) geometries.

As illustrated in Figure 6, in a resonator laser design 100 a photonic crystal fibre 102 is located in line in a ring laser 104 (of any sort) to improve both linewidth, laser stability and mode selectivity (including transverse if multi-mode active fibre is used to increase power). It is noted that a similar design can be applicable to linear lasers (of any sort).

As illustrated in Figure 7, in an alternative embodiment, a helical ring fibre laser 110 comprises an

optical fibre 112 having a grating confined core structure 114 and spaced apart concave reflectors 115, 116 within the core structure 114. The helical ring fibre laser 110 can thus provide a circularly birefringent output (as indicated by arrow 111).

Furthermore, high power fibre lasers may be provided without using cladding pump configuration. For such lasers, single mode operation and good stability are possible, as well as large mode areas. In such embodiments, the modes are grating diffraction dependent unlike conventional fibres which are aperture diffraction dependent.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

The claims defining the invention are

1. An optical device comprising:

- a waveguide of photosensitive material;
- at least one grating structure formed by UV-induced refractive index variations in the waveguide; and

wherein the grating structure is disposed to confine to a selected path in the waveguide light of a predetermined wavelength entering the waveguide at a predetermined angle of incidence on the grating structure.

2. A process for fabricating an optical device comprising a waveguide of photosensitive material, the method comprising the step of:

- forming at least one grating structure by UV-induced refractive index variations in the waveguide; and

wherein the grating structure is disposed to confine to a selected path in the waveguide light of a predetermined wavelength entering the waveguide at a predetermined angle of incidence on the grating structure.

Dated this 27th day of August 1999

The University of Sydney

By their Patent Attorneys

GRIFFITH HACK

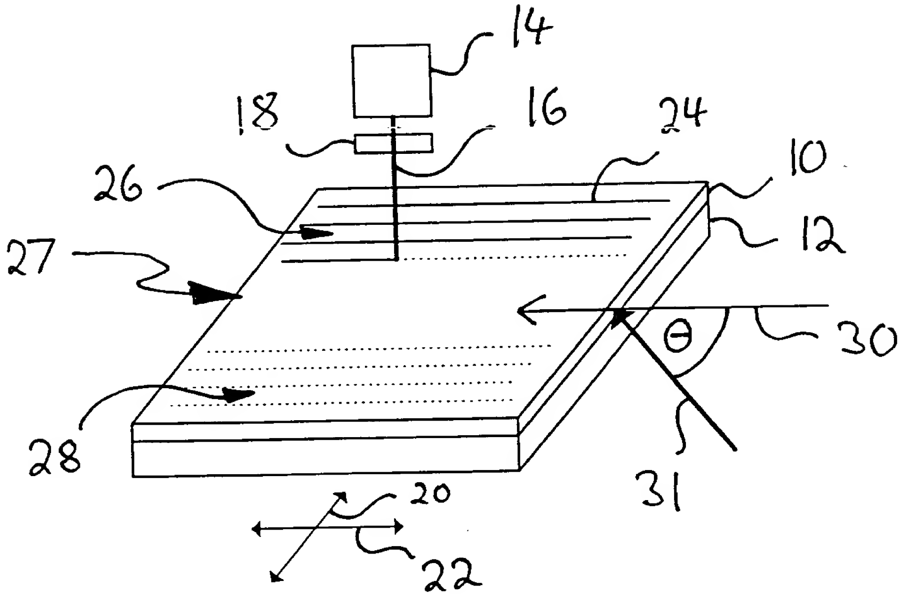

Figure 1

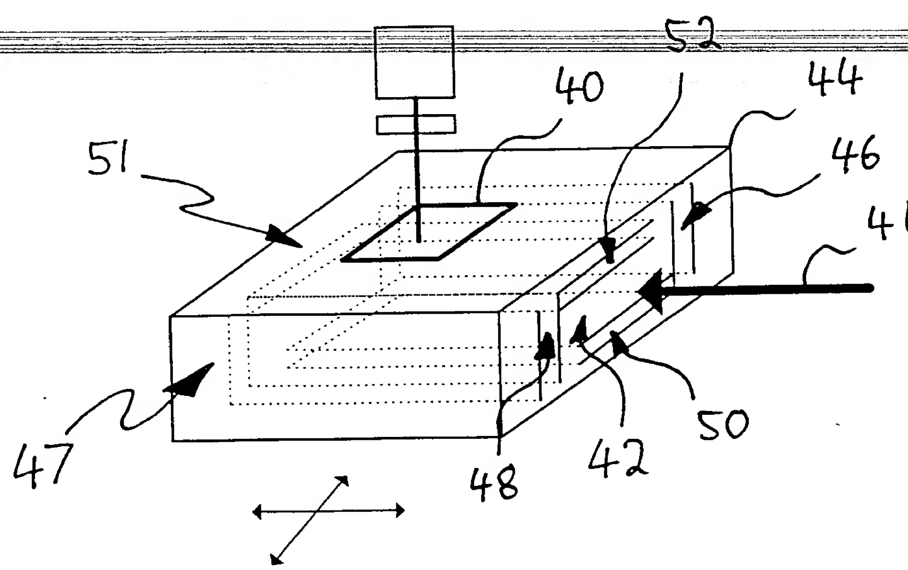

Figure 2

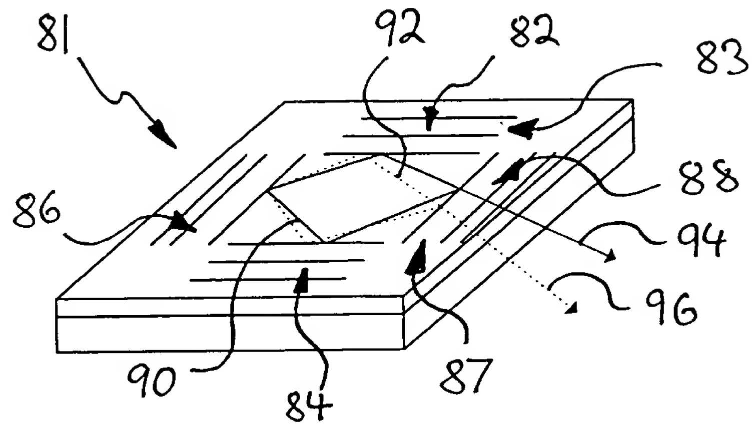

Figure 5

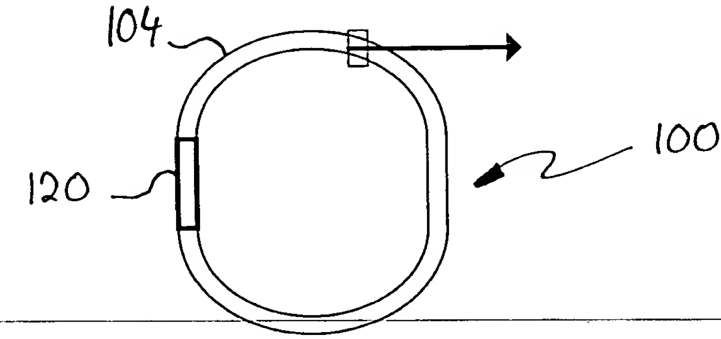

Figure 6

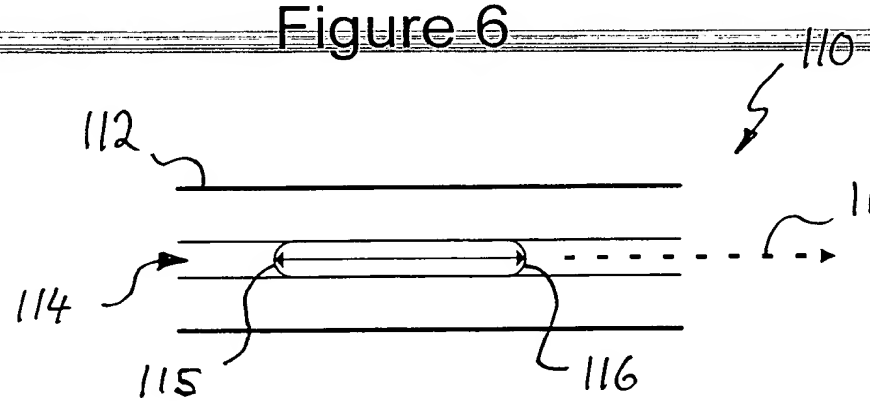

Figure 7

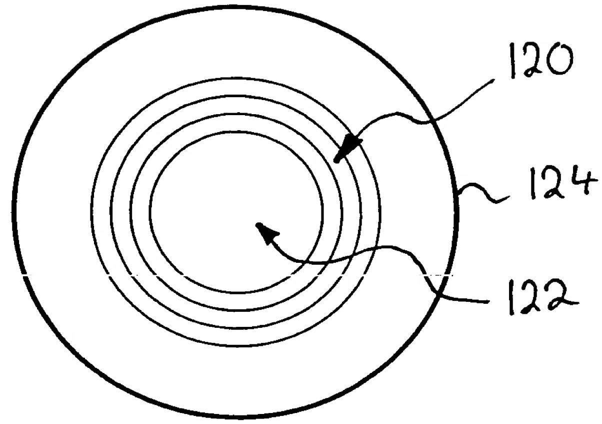

Figure 3

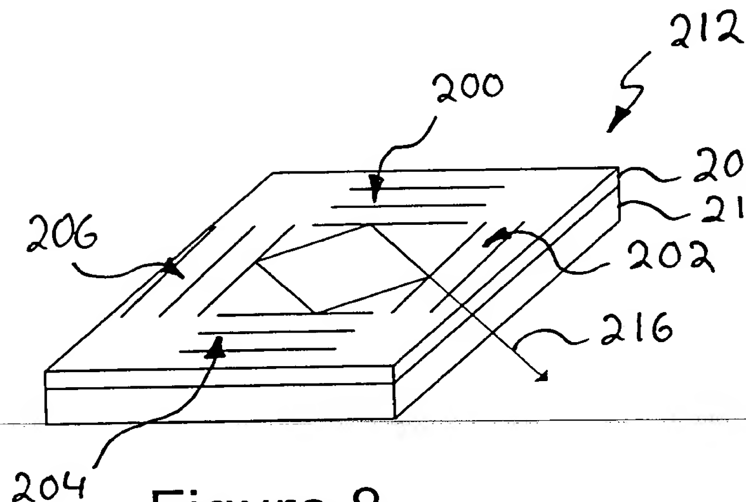

Figure 8

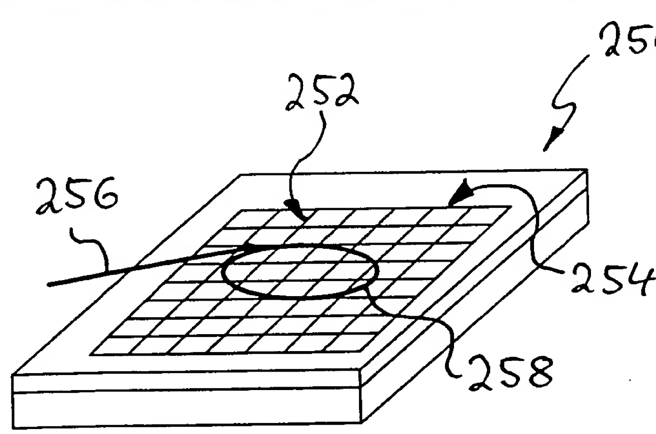

Figure 9

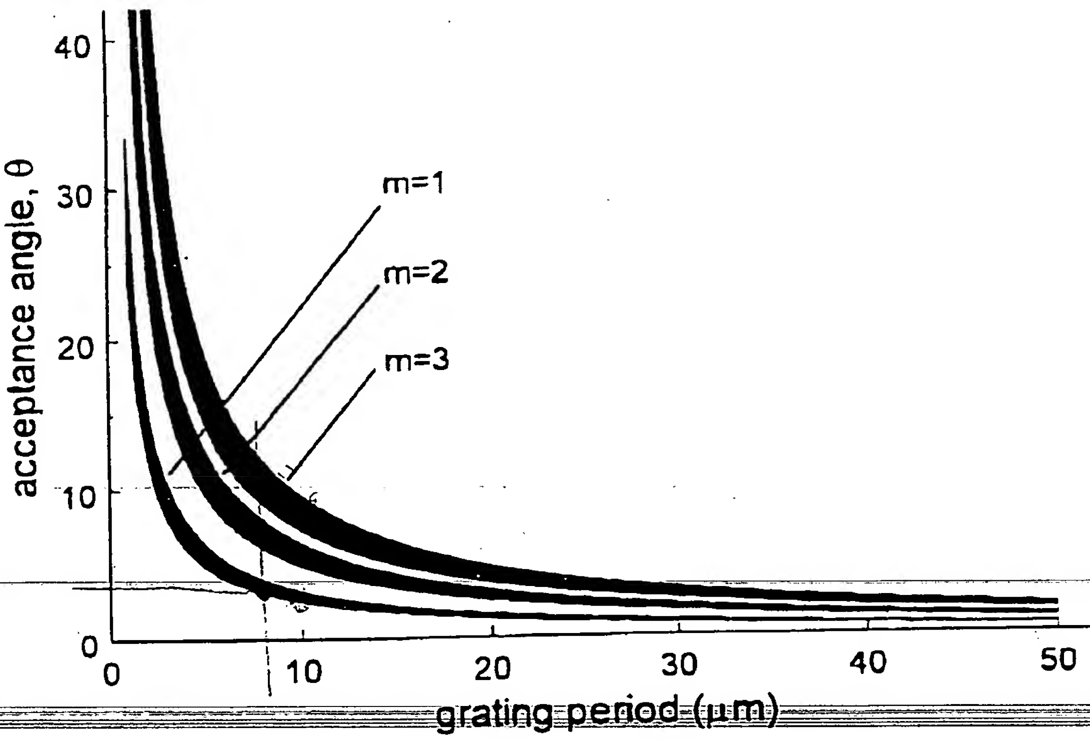
acceplance angle, θ
40
30
20
10
0
m=1
m=2
m=3
0
10
20
30
40
50
grating period (μm)

Figure 4